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ABSTRACT

The two-frequency rocket-borne propagation experiment of Seddon has recently been used to measure the electron density distribution well above the F_2 peak of the ionosphere. For these high-altitude measurements of local electron density, the effects of the variation in the electron density distribution along the ray path have to be considered. Even for a quiet ionosphere a correction has to be made due to the curvature of the trajectory and the curvature of the earth, since for practical reasons vertical rocket firings cannot be realized.

An example of a measurement of the electron-density profile up to 620 km by means of the CW propagation technique is presented. The correction of the local electron density due to the geometry of the trajectory for a launching 10 degrees off the vertical amounted to about 20% at an altitude

of 620 km. From the corrected electron density profile other parameters such as scale height and temperature of the upper ionosphere can be inferred.

For the anticipated measurements up to an altitude of one earth radius using the CW propagation experiment and vehicles of the Scout type, the time variation of the ionosphere below the vehicle must always be considered to arrive at reliable local electron density data. A correction for this time variation can be made by using recorded information on the ordinary and extraordinary propagation modes at two harmonically related frequencies. This correction procedure is briefly outlined.

Future measurements up to a few thousand kilometers should allow the determination of the electron density distribution with height, especially in the transition-region from the ionosphere to the protonosphere.

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The rocket-borne CW propagation technique for measuring ionospheric electron density introduced by Seddon (1953) is based upon the measurement of the dispersive Doppler effect at two harmonically related frequencies f and 6f. This Doppler effect is the result of the motion of a rocket-borne transmitter within the ionosphere and can be expressed as a change in the phase path P of the transmitted radio wave

$$\dot{P} = \frac{2\pi f}{c}\left[n_R \dot{r} + \int_0^R \frac{dn}{dt} \, dr \right] \tag{1}$$

where f is the transmitted frequency, c is the velocity of light in vacuo, n_R is the refractive index at the rocket which is related to the electron density N through the Appleton-Hartree formula and $\dot{r}$ is the velocity component of the rocket in the ray-direction. The integral term represents the time variation of the refractive index (or electron density) along the ray path. For low altitude flights and nearly vertical rocket firings as was the case in earlier experiments, the latter term is, in general, negligibly small. However, with the extension of the CW propagation experiment to higher altitudes and more oblique propagation paths, the integral term must be considered as a correction term to arrive at accurate local electron densities.

In the following discussion we shall consider CW propagation measurements by means of research-rockets reaching altitudes well beyond the F_2 peak of the ionosphere.

The experimental arrangement used for these measurements is the following:

The rocket payload consists of a transmitter delivering the two harmonically related frequencies $f = 12.267$ Mc/s and $6f = 73.6$ Mc/s with a frequency stability of 1 part in 10^8, and two dipole antennas for these frequencies which are extended telescopically to their full lengths (21 and 7 ft. tip-to-tip, respectively) by explosive charges after nose-cone ejection. Fig. 1 shows the payload with the antennas extended. Prior to nose-cone ejection the antennas are folded along-side the payload frustum and therefore do not provide effective radiation, especially at the lower frequency. For this reason actual measurements begin only after nose-cone ejection and antenna deployment. A rather complex ground station (Fig. 2) located near the launching site is used to receive and compare the signals transmitted from the rocket.

The basic quantities measured at the ground station are the beat frequencies due to the difference between the received high frequency 6f and low frequency f, the latter multiplied by the harmonic factor ($m = 6$) at the ground, for the two magneto-ionic components, which are separated by virtue of their polarization using proper antenna arrangements.

The beat frequencies obtained by the ground-station equipment can be expressed by

$$(FB)_{o,x} = \frac{6f}{c}\left[(n_{o,x}^{(h)} - n_{o,x}^{(\ell)})\dot{r} + \int_0^R \frac{d}{dt}\,(n_{o,x}^{(h)} - n_{o,x}^{(\ell)})dr\right] \pm \text{roll correction} \qquad (2)$$

where $n^{(h)}$ is the refractive index at the high frequency 6f, $n^{(\ell)}$ is the index at the low frequency f and the subscripts o and x refer to the ordinary and extraordinary components, respectively, while the other quantities have their previously defined meanings. The first term of (2) is related to the electron density at the rocket, while the second term represents a correction due to the time variation of the electron density distribution along the ray path. The ordinary and extraordinary beat frequencies, as well as their algebraic combinations are directly available from the ground station.

For a recent experiment, which shall be discussed here as an example, the analysis was based upon the sum of the ordinary and extraordinary beat frequencies which may be expressed as a first approximation by

$$F_s = \frac{6f}{c} \left[(n_o^{(h)} + n_x^{(h)}) - (n_o^{(\ell)} + n_x^{(\ell)}) \right] \dot{r} \qquad (3)$$

The sum F_s has the advantage of being free of roll effects since the individual ordinary and extraordinary beat frequencies have equal but opposite roll corrections. Furthermore, F_s is almost independent of the earth's magnetic field over the altitude and electron density range covered by the present experiment. However, the consistency of the obtained data can be checked by analysis of the individual ordinary or extraordinary beat frequencies. The roll rate of the rocket needed for correcting the individual beat frequencies is also obtained at the ground station from the received high frequency signal, after a slight correction for the Faraday-rotation at this frequency.

From F_s an apparent local electron density corresponding to

$$N' = \frac{1}{\Delta r} \left(\int_0^{P_2} N dr - \int_0^{P_1} N dr \right) \qquad (4)$$

can be obtained by means of the Appleton-Hartree formula together with trajectory information giving the radial velocity component of the rocket.

The reason why the electron densities obtained in this manner are not true local electron densities is because the integral term was neglected in the expression for F_s (equ. 3). For a quiet ionosphere, i.e. no rapid changes in the electron density distribution along the ray path and absence of significant horizontal gradients, the integral term is mainly due to the geometry of the trajectory. For a spherically stratified ionosphere, the true electron density can be derived from the apparent electron density on the basis of the following correction procedure which follows from simple geometrical considerations (Fig. 3):

$$N = N' + \frac{\varepsilon}{1-\varepsilon} \ (N' - \overline{N}) \tag{5}$$

with $\varepsilon = \dfrac{\dot{\theta}\ r \tan \theta_r}{\dot{r}}$, where θ is the zenith angle of the position vector at the ground station and θ_r is that angle at the rocket, r is the radial distance between ground station and rocket as defined by Fig. 3 and

$$\overline{N} = \frac{1}{r} \int_0^r N \, dr \cong \frac{1}{r} \int_0^r N' \, dr$$

The results of the electron density measurements of a recently fired 4-stage research rocket of the type ARGO D-4 are shown in Fig. 4. The dashed line represents the apparent (uncorrected) electron density profile obtained from the sum F_s of the ordinary and extraordinary beat frequencies based on equation (3), while the solid line represents the electron density profile after applying the obliquity correction outlined above. For this particular case, the simplified correction procedure was applicable, since the ionosphere was very quiet during the firing and no horizontal gradients were indicated from the vertical incidence soundings of the ionosphere at three stations in the neighborhood of the launch site.

Although the obliquity correction at 620 km (which is about 85% of the particular peak altitude and the altitude where the vertical velocity component of the rocket became comparable to the horizontal component), is only of the order of 20%, the importance of this correction becomes apparent when one tries to interpret the physical significance of an electron density profile. On the basis of the uncorrected profile one could deduce a positive scale height gradient with the implication of increasing temperature in the height region above the F_2 peak, while the actual profile based on the corrected electron density is representative of a diffusive equilibrium distribution in an isothermal upper ionosphere. It should be noted that a number of the published electron density profiles above the F_2 peak obtained from rocket measurements using propagation techniques resemble our uncorrected profile. This suggests that the correction outlined here may not have been made and that caution should be taken in the geophysical interpretation of such profiles. From the practically constant logarithmic slope of our electron density distribution above the F_2 peak a scale height for the electron-ion gas of the order $H' \doteq 200$ km is obtained. Assuming local thermodynamic equilibrium and the major ionic constituent to be atomic oxygen, this scale height corresponds to a temperature $T \doteq 1640^{\circ}K$ for the altitude region from 350 to 620 km, which is in good agreement with daytime temperatures derived from satellite density data (Jackson and Bauer, 1961).

While for a quiet ionosphere, as shown by the present example, the simplified correction procedure (based on geometrical considerations only) for obtaining local electron densities from CW propagation measurements is applicable, this is not the case for times when the ionospheric electron density distribution varies rapidly with time, e.g. at sunrise or during ionospheric disturbances. Furthermore, for altitudes well above 1000 km the integral term in equation (2) can assume major importance even for almost vertical firing since the contribution of the time-varying integral term may become comparable in magnitude to the first term representing the local electron density.

In principle, the integral term can be eliminated if simultaneous Doppler and Faraday-rotation measurements are being made, as first suggested by Kelso (1960). For high frequencies this procedure is relatively straightforward. For frequencies as low as 12.267 Mc/s which provide a more sensitive measure of the ionospheric electron density, a simple approximation to the Appleton-Hartree formula is not sufficient for an accurate determination of the local electron density. However, with all the quantities measured in the CW propagation experiment, it is possible to arrive at a solution for the local electron-density at the rocket, based on the complete Appleton-Hartree formula, taking into account the effect of a time-varying electron density distribution along the ray path.

The following two quantities are directly obtainable from the CW propagation experiment:

$$\Sigma = \frac{mf}{c}\left[\mathcal{N}_1 \dot{r} + \int_0^R \frac{d}{dt} \mathcal{N}_1 \, dr\right] \tag{6}$$

$$\Delta = \frac{mf}{c}\left[\mathcal{N}_2 \dot{r} + \int_0^R \frac{d}{dt} \mathcal{N}_2 \, dr\right] \tag{7}$$

where $\mathcal{N}_1 = (n_o^{(h)} + n_x^{(h)}) - (n_o^{(\ell)} + n_x^{(\ell)})$ and

$\mathcal{N}_2 = (n_o^{(\ell)} - n_x^{(\ell)}) - (n_o^{(h)} - n_x^{(h)})$

and the other quantities have their previously defined meanings.

The quantities $\mathcal{N}_1$ and $\mathcal{N}_2$ are expressed in terms of the refractive indices given by the complete Appleton-Hartree formula. It is convenient to represent $\mathcal{N}_1$ and $\mathcal{N}_2$ graphically as a family of curves.

Setting $\mathcal{N}_1 = \lambda \mathcal{N}_2$

where $\lambda(N, \vec{H})$ is a parameter which depends upon the electron density N and the earth's magnetic field $\vec{H}$, we can now write:

$$\lambda \mathcal{N}_2 \dot{r} + \bar{\lambda} \int_o^r \frac{d\mathcal{N}_2}{dt} dr = \frac{c}{mf} \Sigma$$

$$\mathcal{N}_2 \dot{r} + \int_o^r \frac{d\mathcal{N}_2}{dt} dr = \frac{c}{mf} \Delta$$

where $$\bar{\lambda} = \frac{\int_o^r \mathcal{N}_1 dr}{\int_o^r \mathcal{N}_2 dr}$$

and $\int_o^r \mathcal{N}_1 dr$ and $\int_o^r \mathcal{N}_2 dr$ can be computed by numerical integration from the complete Appleton-Hartree formula on the basis of the measured electron density profile, uncorrected for the time variation along the ray path.

From the two above equations we obtain

$$\mathcal{N}_2 = \frac{c}{mf} \left[\frac{\Sigma - \bar{\lambda}\Delta}{(\lambda - \bar{\lambda})\dot{r}} \right] \tag{8}$$

The local electron density at the rocket can now be determined from $\mathcal{N}_2$ by means of the complete Appleton-Hartree formula.

It should be noted that the general correction outlined above, includes the time variation of the electron density distribution along the ray path due to the geometry of the trajectory as well as the explicit time variation of the ionosphere. Although in principle, the general correction could be applied to rocket flights below 1000 km, such as the one illustrated earlier, the procedure is more complicated because of the additional evaluation of the beat-frequency difference Δ, as well as the roll correction. Furthermore, for a quiet ionosphere it does not improve the accuracy of the local electron density above that obtained by means of the relatively simple obliquity correction.

The previous discussion is based on rather idealized conditions. However, with research-rockets, near-vertical firings with zenith angles of 4^{o} to 10^{o} can be realized. Thus, problems like refraction or path-splitting of the ordinary and extraordinary propagation modes do not become as serious,-at least not on the upward leg of the trajectory which is mainly used for the CW propagation experiment-as in satellite propagation work. If the need arises, the more complicated situation can be considered by ray tracing procedures using electronic computers as has been shown for satellite propagation studies (Little and Lawrence, 1960). A detailed theoretical discussion of propagation phenomena in a time varying inhomogenous ionosphere applicable to rocket and satellite measurements has recently been given by Kelso (1961).

The upper limit for the propagation experiment is mainly determined by the magnitude of the beat frequency and the applicability of the correction procedure. Theoretically derived beat-frequencies based on estimates of ionospheric structure and vehicle performance for the ARGO D-4 and the Scout vehicle are shown in Fig. 5. It can be seen, that for the Scout the beat frequency drops to 1 cps at about 800 sec after take-off corresponding to an altitude of about 4000 km. However it is possible, to average the readings of beat frequency over longer time intervals, so that it appears feasible to make useful measurements to even greater altitudes. The time period over which the beat notes are read may be of the order of several seconds which still corresponds to a height interval small compared to the local scale-height which is of the order of $\sim$1000 km due to the predominance of hydrogen at altitudes above 2000 km.

Measurements with the Scout vehicle should make it possible to measure with good accuracy the electron density distribution in the transition-region from ionosphere to protonosphere, and with reasonable accuracy the electron densities within the protonosphere.

To make full use of the rocket vehicle a direct-measurement technique, such as an RF-impedance probe is included which measures electron density on the downward leg where the propagation experiment is handicapped because of the oblique propagation paths. The propagation experiment also provides in-flight calibration on the upward leg for the direct measuring technique, since, e.g. the RF-probe at the present time has not yet achieved the degree of measurement accuracy (±2%) which can be realized with the propagation technique under undisturbed conditions.

The CW propagation technique which has in the past proven itself a useful tool for ionospheric research may also find application in the future exploration of planetary ionospheres.

ACKNOWLEDGEMENT

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ARGO D-4 PAYLOAD WITH ANTENNAS EXTENDED
(SCOUT PAYLOAD WILL BE SIMILAR.)

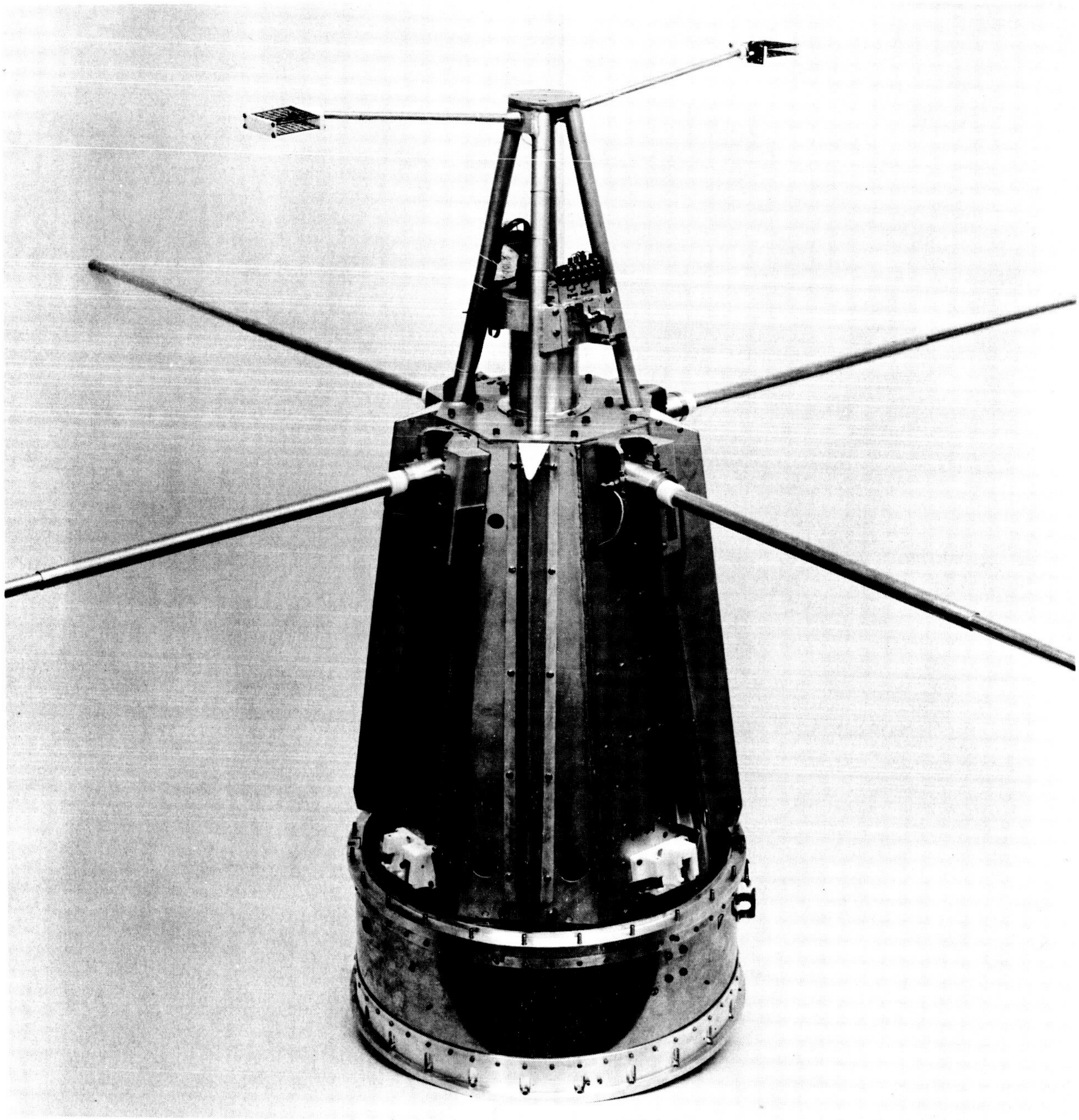

FIG. 1

GROUND STATION

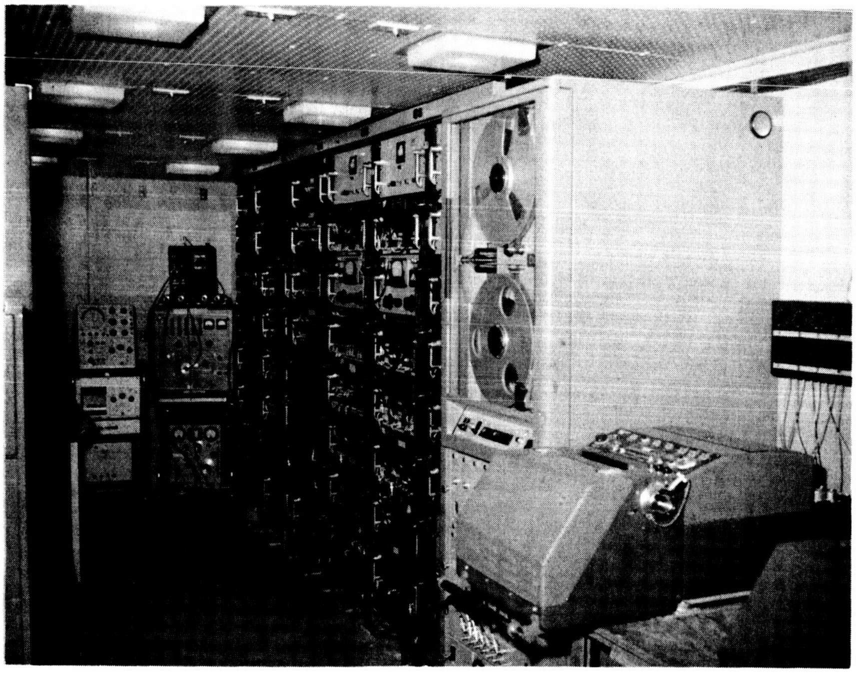

FIG. 2

GEOMETRY FOR OBLIQUITY CORRECTION

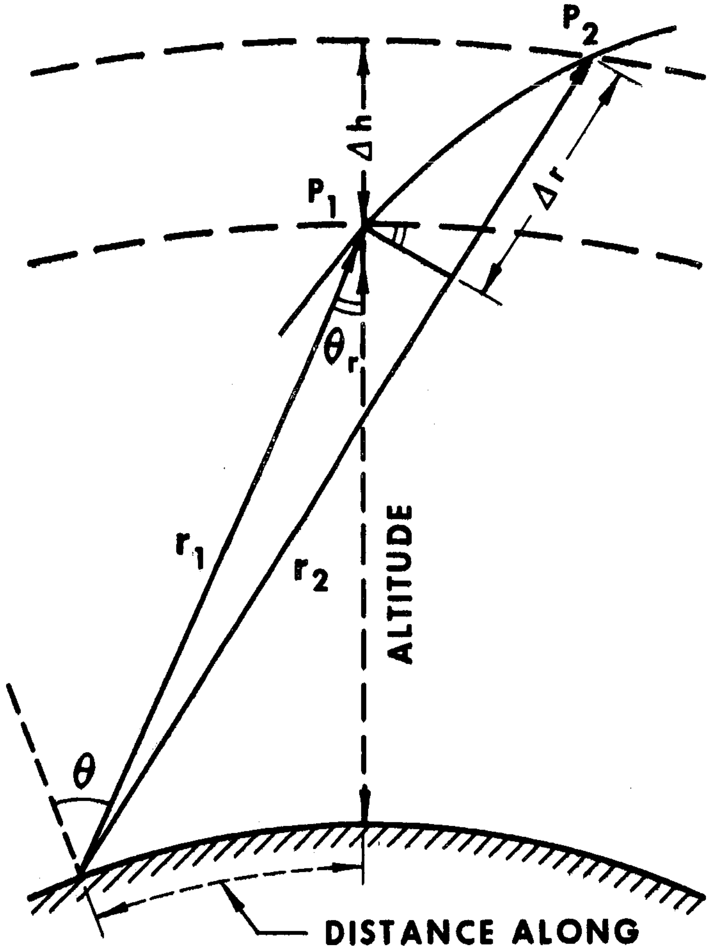

FIG. 3

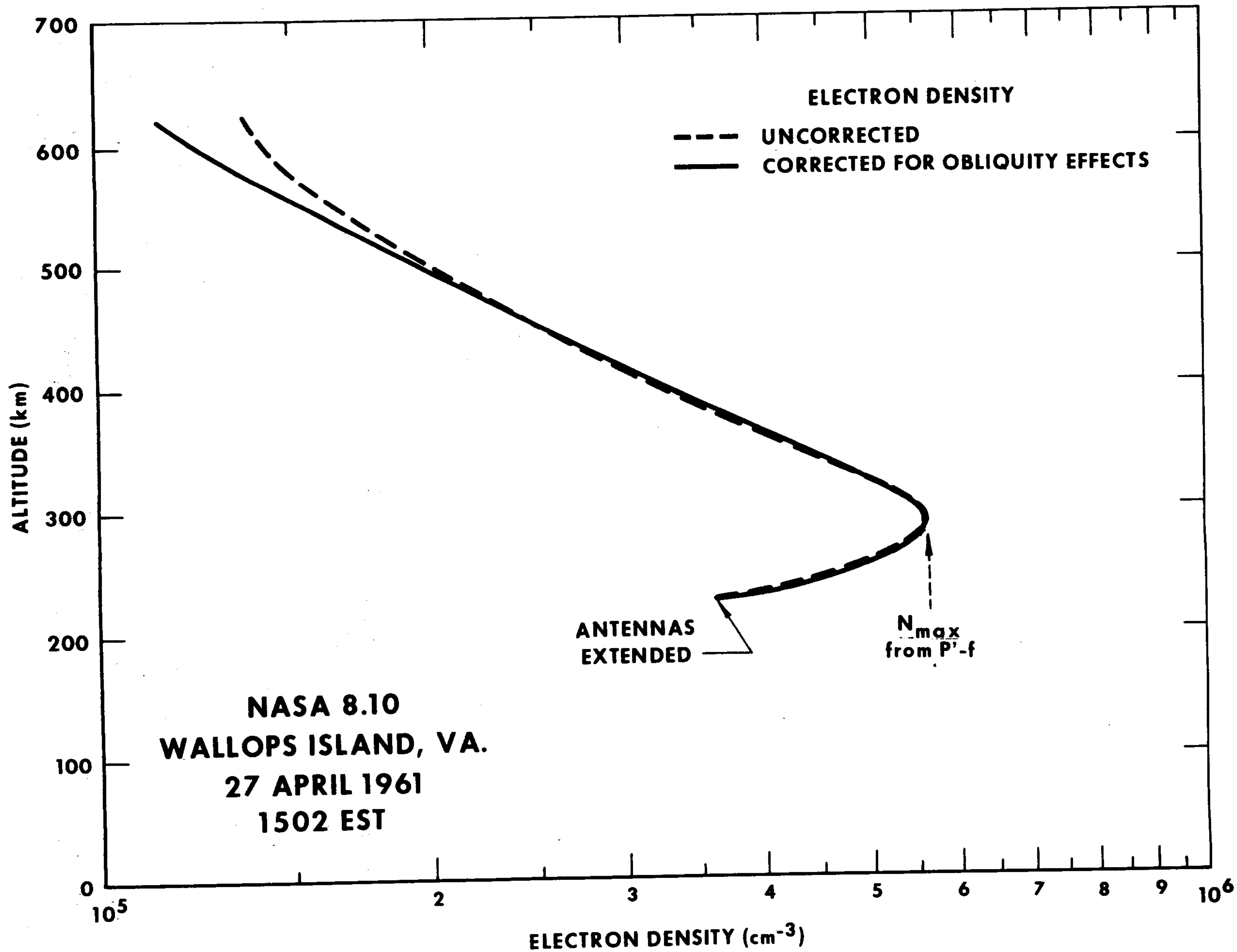
700
600
500
400
300
200
100
0
ALTITUDE (km)
ELECTRON DENSITY
UNCORRECTED
CORRECTED FOR OBLIQUITY EFFECTS
ANTENNAS EXTENDED
N max from P'-f
NASA 8.10
WALLOPS ISLAND, VA.
27 APRIL 1961
1502 EST
10^5
2
3
4
5
6
7
8
9
10^6
ELECTRON DENSITY (cm^-3)

FIG.4

EXPECTED BEAT FREQUENCY VERSUS TIME

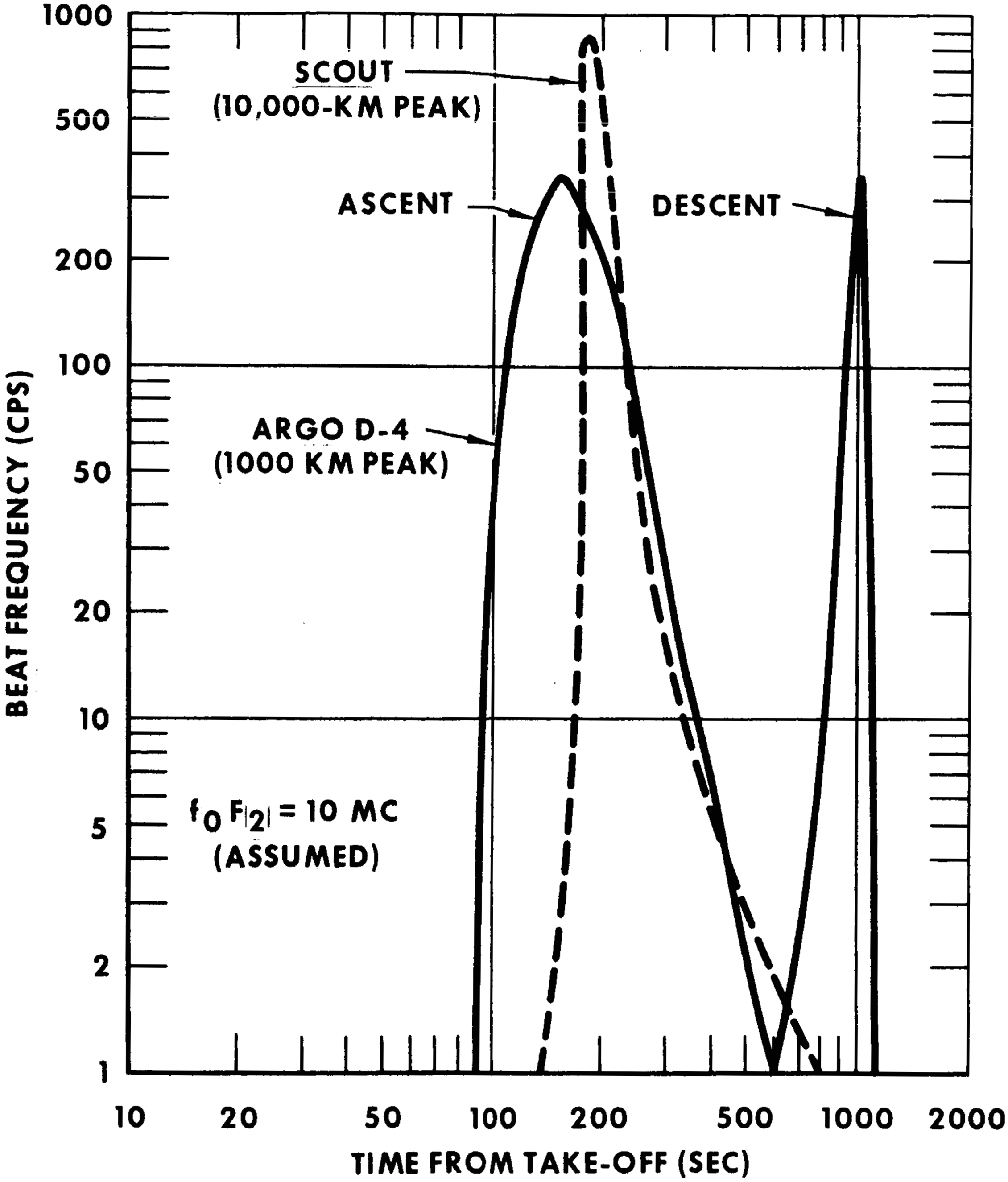

FIG. 5